Canadian Committee for Antarctic Research
Comité canadien de recherches antarctiques

SUBGLACIAL LAKE AND DEEP ICE EXPLORATION: CANADIAN EXPERTISE AND INTERNATIONAL OPPORTUNITIES

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Canada

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Foreword 1

1 Opening Statements

1.1 Welcome 2
Olav Loken

1.2 Background and rationale for workshop 2
Warwick Vincent

2 Current and Future Research Activity on Subglacial Lakes and Deep Ice

2.1 International activities 4

International Opportunities for Subglacial Lake Exploration 4
Mahlon C. Kennicutt II

Lake Vostok (Antarctica) Ice Core Studies 6
Jean Robert Petit

The Physiography of Modern Antarctic Subglacial Lakes 8
Martin J. Siegert

2.2 Canadian activities 11

Life in Lake Vostok 11
David Bird

A Proposal for Sampling a Subglacial Lake at South Pole 13
Erik Blake

Lake Vostok as Tabula Rasa and Multidisciplinary Challenge 15
Garry K. C. Clarke

Ice Core Records from the Canadian Arctic and Yukon 17
David A. Fisher and Roy (Fritz) Koerner

Modelled Inception and Growth of the Antarctic Ice Sheet
Nested Model Examination of Subglacial Energy Balance in the Vostok Region 18
Shawn J. Marshall

Subglacial – Deep Ice Research Activities 20
Wayne Pollard

Microbial Activity Beneath Ice Sheets and its Influence on the Subglacial Environment 20
Martin Sharp
Julia Foght

Virus Indicators in Deep Ice and Sub-glacial Lakes as Indicators of Global Change 22
Curtis Suttle

Polar Microbial Ecology 23
Warwick F. Vincent

3.0 Advancing Canadian Interests in Subglacial Lake and Deep Ice Research in Antarctica 24
Nicole Couture

4.0 Closing Remarks 27
Warwick Vincent

References Cited 28

Appendix A - Workshop Participants 33

Appendix B - List of Acronyms 36

Foreword

Scores of subglacial lakes exist beneath the East Antarctic Ice sheet. Much of the research on such lakes has focussed on Lake Vostok, a large lake beneath almost 4 km of ice. A drilling program established at Vostok Station above the lake has yielded the deepest ice core ever recovered, providing scientists with a detailed record of past climate, as well as information about the sediments and microbes that may well be present in the lake. The international science community is planning further studies and in 1999, the Scientific Committee on Antarctic Research (SCAR) convened a workshop in Cambridge, UK to develop a science plan for the exploration of subglacial lakes.

Canadian scientists have participated in analyses of the material from Lake Vostok, usually through invitations from research groups abroad, mainly the U.S. But no attempt had been made to establish links among interested Canadian scientists. To address this situation, and in the belief that we would all benefit from the synergy of sharing ideas and exploring common interests, the Canadian Committee for Antarctic Research (CCAR) arranged a workshop in March 2001 to bring together Canadian and international scientists having an interest in exploration of subglacial lakes and deep ice. The workshop also responded to a recommendation from the Cambridge workshop that National Antarctic Programs be asked to gauge the interest in their respective countries in subglacial lake exploration.

The Canadian Polar Commission (CPC) provided financial and in-kind assistance for the workshop, and the Department of Foreign Affairs and International Trade (DFAIT) also contributed through its Going Global Science and Technology Program. We gratefully acknowledge this support.

Olav. H. Loken and Nicole Couture
May 2001

1 Opening statements

1.1 Welcome

Olav H. Loken
Secretary, Canadian Committee for Antarctic Research

On behalf of Steve Bigras, Executive Director of the Canadian Polar Commission (CPC), who was unable to attend, Dr. Olav Loken welcomed the participants to the workshop and to the offices of the Commission. The Canadian Polar Commission is responsible for: monitoring, promoting, and disseminating knowledge of the polar regions; contributing to public awareness of the importance of polar science to Canada; enhancing Canada's international profile as a circumpolar nation; and recommending polar science policy direction to government. The CPC represents Canada on the International Arctic Science Committee (IASC) and, since 1994, is Canada's adhering body to the Scientific Committee on Antarctic Research (SCAR). SCAR is responsible for initiating, promoting, and coordinating scientific research in Antarctica, and also for providing science advice to the Antarctic Treaty System.

As the adhering body to SCAR, the CPC is responsible for representing Canada's national interests in Antarctic and bipolar science and for disseminating relevant information to Canada's polar research community. To advise on these and other matters pertaining to research in the Antarctic region and to ensure that the Canadian polar research community participates in critical planning activities and encourages international co-operation in Antarctic and bipolar research, the Commission established CCAR as Canada's National Antarctic Committee under SCAR. As such, CCAR acts as the primary link between the international Antarctic science community and Canadian scientists active in or seeking to become involved in Antarctic and/or bipolar research. It also serves as a national advisory body on Antarctic matters, reporting primarily to the CPC.

1.2 Background and rationale for workshop

Warwick Vincent
Chair, Canadian Committee for Antarctic Research

Drilling of the 3.6 km deep hole in the East Antarctic ice sheet at Vostok Station, the discovery of subglacial Lake Vostok, and reports of live microbes in the deep Vostok ice-core have generated much interest in the international science community and in the public media (SCAR, 2000). These discoveries have raised many questions regarding the physical, chemical and biological nature of the lakes, their history as recorded in the lake sediments, and the potential for life in extreme environments. Over 70 other subglacial lakes have also been identified beneath the Antarctic ice sheet (Siegert et al., 1996). The international Antarctic science community co-ordinated by SCAR is currently formulating plans for further studies and for the eventual sampling of such lakes and the overlying ice. It is therefore timely for Canada to identify its expertise in 'extreme-ice' science and technology, and to explore the potential for Canadian input to international initiatives in these areas.

Over the last few years, Canadians have participated in various aspects of Lake Vostok analysis and discussions. In the period 1999-2000 three Canadian scientists wrote or co-authored papers about Lake Vostok and the ice core from the drill hole. One of these papers (Karl, Bird et al. 1999) counted among the annual "Top 10" list of recent science developments

selected by the editors of *Québec Science*. A Canadian engineering company is playing a key role in an international group developing new instrumentation to collect uncontaminated samples from the ice, the lake water, and the sediments (Blake 2000). Other Canadians participate in projects to advance scientific understanding of the ice systems on Mars and on the moons of Jupiter (e.g., Pollard et al. 2000). The deep ice and subglacial lakes of Antarctica are seen as terrestrial analogues for some of these phenomena elsewhere in the solar system.

Three factors make working on subglacial systems and thick ice attractive, and will likely influence planning and research. The first is multidisciplinarity. The locations of subglacial lakes and deep ice and the nature of their contents make the subject attractive to a wide range of expertise. The diversity of scientific interests represented at this workshop reflects the broad array of potential projects, as do the intersections between disciplines, such as geomicrobiology, hydrogeochemistry and the hydrodynamics of ice-water interactions. Opportunities are therefore available for contributing individual perspectives to a much greater whole in understanding these complex, deep ice-water systems.

Secondly, there are some exciting and fundamental questions within individual disciplines. This is relevant given our individual specialities and long-term research objectives. Although funding agencies increasingly promote multidisciplinarity, maintaining and developing advanced specialized expertise remains essential. Issues arising from the exploration of subglacial lakes and deep ice demonstrate that there may be opportunities to contribute in a fundamental way to questions such as the evolution of microbial life, or the hydrodynamics and geochemistry of ice-water systems. This fundamental knowledge has broad importance that extends well beyond the understanding of phenomena and processes within the polar regions.

Finally, the exploration of subglacial lakes and deep ice has captured the public imagination. When *Science* published three articles and a commentary about Lake Vostok (Jouzel et al., 1999; Priscu et al., 1999; Karl et al., 1999, Vincent 1999), a myriad of newspaper, magazine, radio, TV and web site reports followed. Lake Vostok exploration has many elements that excite the public: a remote, harsh, and until recently hidden environment, an exciting place to get to, links to questions about planetary systems elsewhere and to all sorts of questions about life. This presents a challenge. The increased research activity that comes with high international visibility will likely mean overlap and duplication of expertise, bringing the need to focus on complementary, innovative projects that fit within a greater international program. In this workshop we need to consider how Canada can best make a unique contribution. It is important to identify the kind of expertise Canadians can promote and develop within a greater, internationally co-ordinated system.

The aims of this workshop are to exchange information about Canadian expertise and activities relevant to the study of subglacial lakes and extreme-ice environments, and to examine future plans and opportunities for research in these areas. The specific objectives are:

1) to identify expertise and contacts, and to investigate opportunities for research and exchange in the future. This will include exploring some of the international initiatives that exist and discussing forums in which Canadian representation might be beneficial;
2) to identify shared interests and consider how these interests can best be advanced in both a national and an international context;
3) to evaluate options that need to be developed in order to better coordinate Canadian involvement and international collaboration in the exploration of subglacial lake and deep ice systems.

2. Current and Future Research Activity on Subglacial Lakes and Deep Ice

2.1 International activities

International Opportunities for Subglacial Lake Exploration

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The exploration of subglacial lakes has caught the imagination of the scientific and lay public. The high level of interest has been generated by speculation about the possibility of life in the lake being isolated for hundreds of thousands of years and its potential analogy to other ice covered worlds in the solar system, such as Europa, a moon of Jupiter. Plans by the scientific community to explore subglacial lakes have been advanced by a series of workshops starting in 1996. The article of that year by Kapitsa et al. in *Nature* (Volume 381:684-686) engendered the first wide publicity about the possibility of a large lake under the East Antarctic ice sheet. Subsequent to this article, the presence of the lake was reported during the Rome meeting of the Scientific Committee on Antarctic Research (SCAR). Following several workshops, activities culminated with an international workshop in Cambridge in 1999. From this meeting a scientific plan was produced and suggestions were made for a phased-in approach to implementation of a comprehensive subglacial lake exploration program. This report has been widely distributed (Kennicutt et al, 2000).

The workshop report and science plan suggested that subglacial exploration must be international in participation, interdisciplinary in scope, use non-contaminating techniques for lake entry and sample retrieval, and that Lake Vostok should be the ultimate exploration target. The report recognized that successful exploration of subglacial lakes would require sizeable and sustained resources to attain the wide-ranging scientific objectives of such a program. While a number of specific scientific objectives were described they fall into three categories: the detection and characterization of life in the lake; recovery of the paleo-climate record that may be present; and development of a better understanding of the tectonics of Antarctica. The overarching research theme was how the evolution of life, climate and tectonics interacted to produce the unusual physical/chemical settings now known as subglacial lakes.

As far as implementation of an exploration plan, it was recognized that many challenges would need to be addressed. A mechanism for international coordination would have to be devised to encourage broad participation in the project through sharing of implementation and logistical costs. It was also recognized that significant technological challenges will need to be overcome and that the best approach was a phased-in approach that included funding of corollary or supporting projects (such as aerial surveys), technology development and tests in analogous settings, exploration of smaller lakes, and final entry into Lake Vostok. First entry and exploration might best be accomplished by remote sensing or robotic techniques and sample retrieval may be postponed until after initial exploration efforts have been accomplished.

One area that warrants significant investment is the development of subglacial lake exploration technologies. The remoteness and the difficulty of entering the lake, retrieving water, passing through the lake and retrieving sediment – all of this through four kilometres of ice – in a way that prevents lake contamination, is no small order. It was recognized that much of the technology needed does not now exist. Enabling technologies include access

methodologies (ice drilling), non-contaminating systems and procedures, robotics and in situ sensors, sample retrieval techniques, and miniaturization of sensors and sampling devices. Given these technological challenges it was recommended that more accessible analogous settings in northern regions be used as test sites. Northern ice shelves, frozen lakes, and glaciers may be effective proving grounds for new technologies. As the effort proceeds to Lake Vostok, additional tests on the ice shelves of the southern ocean, in smaller more accessible lakes and other analogous settings, would be appropriate.

The workshop recommendations include SCAR's appointment of an international group of specialists, encouragement of scientists and National Antarctic committees to engender support for the program in their home countries and constituencies, and a request to the Council of Managers of National Antarctic Programs (COMNAP) to assist in technology development and planning of logistics. At the2000 SCAR meeting in Tokyo a Group of Specialists on Subglacial Lakes was formed. As of April 2001, the Group has not officially met. COMNAP has deferred the convening of a technology workshop until the problems are more completely defined. Various countries are forming working groups and advancing the cause of subglacial lakes through their national agencies and support mechanisms. The US will most likely convene a series of workshops to address specific issues related to subglacial lake exploration including sterile entry and sample retrieval methods, drilling technologies, and robotics and in situ sensors.

It is clear that a comprehensive, interdisciplinary subglacial lake exploration program is a major undertaking. It is recognized that the accomplishment of the broad objectives envisioned may well take a decade or more to complete. However, the first steps have already begun. The US has funded improved aerial radar surveys of Lake Vostok and plans are under way to fund a wide array of corollary and supporting projects in other countries. While it may be a while before an international collaborative mechanism is agreed to conduct subglacial lake exploration, interested parties should be developing plans to contribute to the wide range of challenges that will need to be addressed if this ambitious program is to be accomplished.

Lake Vostok (Antarctica) Ice Core Studies

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Ice cores from Greenland and Antarctica provide a wealth of paleoclimate information over a period covering the last glacial interglacial cycles. Proxy of temperature and atmospheric chemical content are deduced from isotopic or chemical composition of the ice. The ice is also unique because of the entrapped air inclusions of fossil air. The Vostok core provides a climatic record covering the last 420 Ky, making it the longest and deepest ice record. During this period, the climate oscillated between glacial and interglacial periods with a 6°C fluctuation in the mean air temperature. Compared to the warm interglacial climates, the glacial periods had a higher dust and aerosol content and the atmosphere contained lower concentrations of greenhouse gas. The record also confirms the influence of solar forcing and demonstrates the importance of greenhouse gases in climatic changes. It also shows that at the time of each deglaciation the southern hemisphere lead the northern hemisphere (Petit et al., 1999).

At the Vostok Station, the drill reached 3623 metres. Below 3310 metres the ice dynamics had disturbed the horizontal layering and the climate record is not available. At 3538 m. the drill penetrated ice with very different properties than the ice sheet above. This ice has a very low electrical conductivity, very large to huge (up to 1 m.) ice crystals, and contains visible (millimetre-size) rock inclusions from the bedrock below. From the isotopic composition of the ice, it has been concluded that it was formed by re-freezing of the lake water to the underside of the ice sheet (Jouzel et al., 1999). This is consistent with the absence of gas in this ice. It was also suggested the bedrock particles were mechanically included in the accreted ice when the ice sheet entered the lake at shallow depth. From a detailed analysis of the isotopic values, Souchez et al (2000) showed the resulting isotopic fractionation during accretion is only 60% the theoretical value. The authors suggested that accreted ice at Vostok is a mixture of low-to-no fractionated frazil ice and fractionated lake water, a phenomenon already observed in ice underneath ice shelves.

X-rays analyses of accreted ice indicate a very high quality of the lattice of the huge monocrystals even for those containing dirt inclusions (Montagnat et al., submitted). The inferred defect concentration is very low and similar to those from laboratory-grown monocrystals. This indicates that accreted ice is not deformed or sheared despite its location at the base of the glacier. On the other hand this supports the concept that accreted ice is just compressed as an ice massif blocked against the lake rim and overlaid by the moving ice sheet (Lipenkov and Barkov, 1998).

Information on the geothermal heat and the possible mantellic emission from the bedrock has been deduced from the helium content of the ice. Helium diffuses through the ice lattice and the distribution within the ice reflects the equilibrium between the different nearby sources (e.g. the atmosphere and the bedrock). The accreted ice at Vostok, representing a contribution of ^{4}He from the crust or crustal derived sediments, contains twice as much ^{4}He (a daughter from U series) as the ice in the overlaying ice sheet. On the other hand, the content of ^{3}He, an isotope generally present in hot springs and ocean smokers, displays no significant changes. This suggests the absence of high enthalpy phenomenon at the bottom of the lake (Jean Baptiste et al., in press). In other words, the rift area in which Lake Vostok is located is likely to have been inactive for a very long time. This is consistent with the old cratonic nature of East Antarctica.

The accreted ice also offered opportunities for biologists and chemists to investigate material from the subglacial lake. Two recent studies suggested presence of low to high bacteria concentration in accreted ice (Priscu et al, 1999, Karl et al, 1999). PCR analyses show that some are very similar to those observed in the glacier ice at different depths (Abysov et al, 1998) supporting their possible transfer from the surface to the lake through the ice sheet. However, given the absence of sterile drilling procedures, the possibility exists that accreted ice microbes are contaminants, despite the care taken to process the inner part of the ice core. Several tests suggest the content of some chemical to be over-estimated, e.g. total organic carbon (by a least one order of magnitude), and ammonia concentrations in nitrates and in nitrites also being too high (Petit et al., unpublished). This uncertainty about the results from prior investigations does not exclude the possibility that Lake Vostok may contain some microorganisms, and obviously more investigations are needed. Stringent decontamination and control similar to those planned for extraterrestrial samples need to be applied. For the Vostok ice, chemical measurements at each step of the ice decontamination and samples processing may add confidence to the biological results.

Marine sediments depicted a warm climatic period (so called stage 11) of unusual duration compared with the other interglacials. There is some interest in documenting this period at circa 450,000 BP: solar forcing was lower than during the following period, and we do not understand why the climate switched to this particular state. A key question is what role the atmospheric greenhouse gases played in climate warming. This is of interest since stage 11 can be seen as an analogue to our future climate because the orbital position of the earth will assume a similar configuration in the near future.

The Vostok ice core provides the longest and deepest ice record because of its glaciological setting at a location with 3750 m of ice. Moreover, Vostok lies not on a dome, but rather on a stream line 300 km downstream from the Ridge B area, which has a higher accumulation rate than the Vostok area. Since the deep ice originated from Ridge B, it compensates the ice thinning significantly. The deep part of the core provided a climatic record with a significant resolution (1000 years per 1m at 3300m depth). It may be possible to extend the climate record from an ice core beyond 400,000 BP, by selecting a new site in the Vostok area, with an ice thickness greater than 3750 m. Such a site exists in the northern part of Lake Vostok where the ice thickness is 4,100 m.

Two current deep drilling projects, EPICA (European Project for Drilling in Antarctica) and Japanese Dome F project, are located on separate ice domes. This choice makes the ice chronology easier to establish, but the deep ice shrinks rapidly below 2000 metres. In this context, a new project for ice coring in the northern lake Vostok area may be a useful complement to the Dome studies. The glaciological setting of this area could be unique among polar ice caps: it has potential for obtaining a very long atmospheric record and also for providing the highest resolution for ice older than 200,000 BP.

It is also interesting to point out that in the northern part of the lake, where the ice is thickest, the ice sheet melts, while lake water freezes onto the ice sheet in the southern area (e.g. Vostok core). The melting area of the lake is of interest for biological studies in providing gas and mineral salts from aerosols that may be important for sustaining biological activity in the lake or in the nearby sediments.

From a scientific point of view, the northern area of Lake Vostok seems very attractive for at least two reasons: the possibility of obtaining climate data from the ice core, and for in-situ lake exploration from an access hole. From a technical point of view, it is not yet clear

whether the two must be pursued separately or if some technology or logistics could be combined.

The Physiography of Modern Antarctic Subglacial Lakes

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There is little doubt now that lakes exist beneath the Antarctic Ice Sheet (Siegert, 2000). Subglacial lakes were first observed on airborne 60 MHz radio-echo sounding (RES) records as extensive areas of smooth and very strong returns from the glacier bed, below several thousand meters of ice (Oswald and Robin, 1973; Siegert et al. 1996). These areas are specular or mirror-like reflectors, with an echo strength that is 10-20 dB above the more usual values associated with an ice-rock interface. Such reflectors are characteristic of a water surface. The spatial coincidence of flat regions on the ice surface with strong, specular radio-echo returns from the ice-sheet bed has been demonstrated in several areas of Antarctica (Siegert and Ridley, 1998a, 1998b). This implies that satellite radar altimetric identification of flat areas on the ice surface can be used to infer the presence of subglacial water bodies. Seismic investigations identified a lake-bed reflector at about 510 metres beneath the subglacial surface of Lake Vostok in East Antarctica (Kapitsa et al., 1996). More recently, Gorman and Siegert (1999) have shown, from radio-echo returns that penetrate to a shallow lake-bottom reflector at several subglacial-lake margins, that the lakes are indeed bodies of fresh water and are not simply very flat areas of saturated basal sediment.

Over 70 subglacial lakes have been identified beneath the 13 million km^2 Antarctic Ice Sheet (Figure 1). Almost 60% of lakes are found within 200 km of an ice divide, remembering that ice flowlines from crest to coastal margin are often over 1,000 km in length. Only about 15% of subglacial lakes are located more than 500 km from an ice divide. The total volume of water stored in lakes beneath the Antarctic Ice Sheet is estimated to be between about 4,000 and 12,000 km^3 (Dowdeswell and Siegert, 1999).

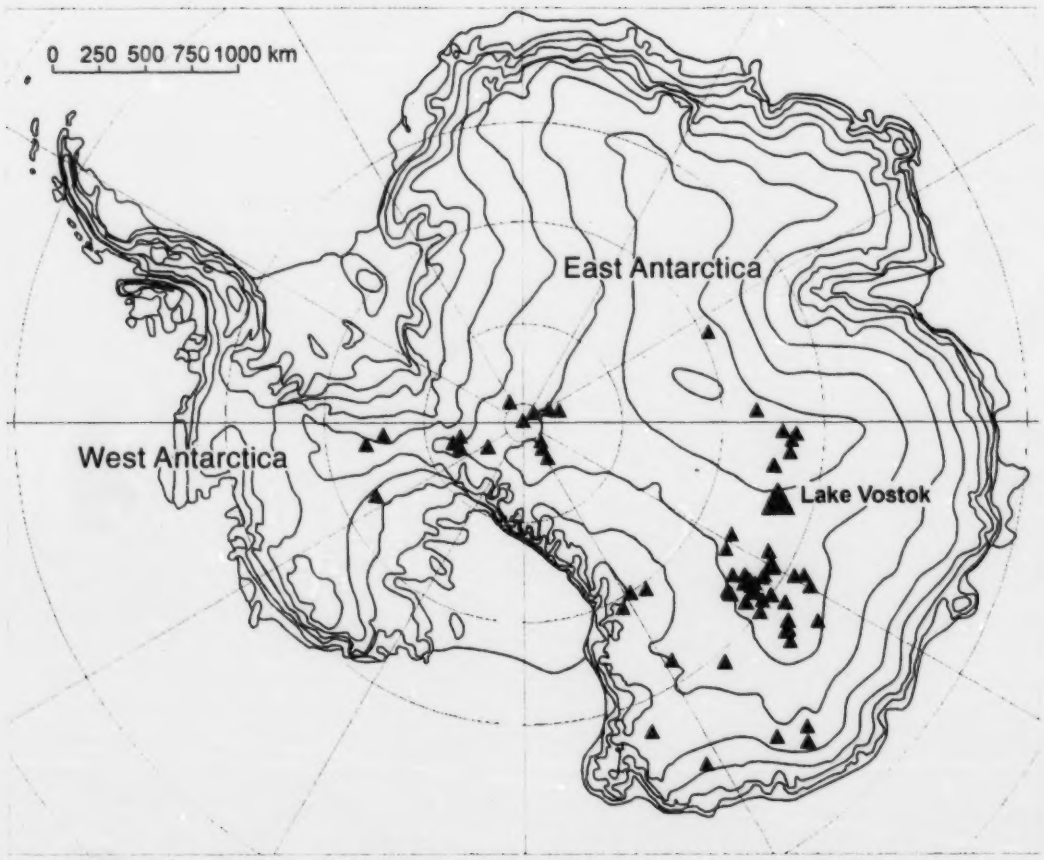

Figure 1: The location of Antarctic subglacial lakes (after Siegert et al. 1996).

The bedrock topography of the ice-sheet interior is characterized by large subglacial basins separated by mountain ranges. More than 60% of lake records have maximum local bedrock elevations of <400m adjacent to their margins and bed gradients of less than 0.1, implying that many Antarctic sub-glacial lakes are found in areas of relatively low bed relief. Over 40 subglacial lakes are concentrated around Dome C, and over 80% of these are found in relatively subdued bedrock topography within large subglacial basins. Lake Vostok, near Ridge B, appears to be located in a topographic basin, with relatively lower slopes to the east and steeper terrain to the west (Kaptisa et al., 1996; Siegert et al., 2000).

Many lakes are found in and on the margins of subglacial basins. First, there are those located where subglacial topography is relatively subdued, often towards the centre of subglacial basins. Secondly, some lakes occur in significant topographic depressions, often closer to subglacial basin margins, but still near the slow-flowing centre of the Antarctic Ice Sheet. Lakes are also found perched on the flanks of subglacial mountains, mainly in the interior of the ice sheet.

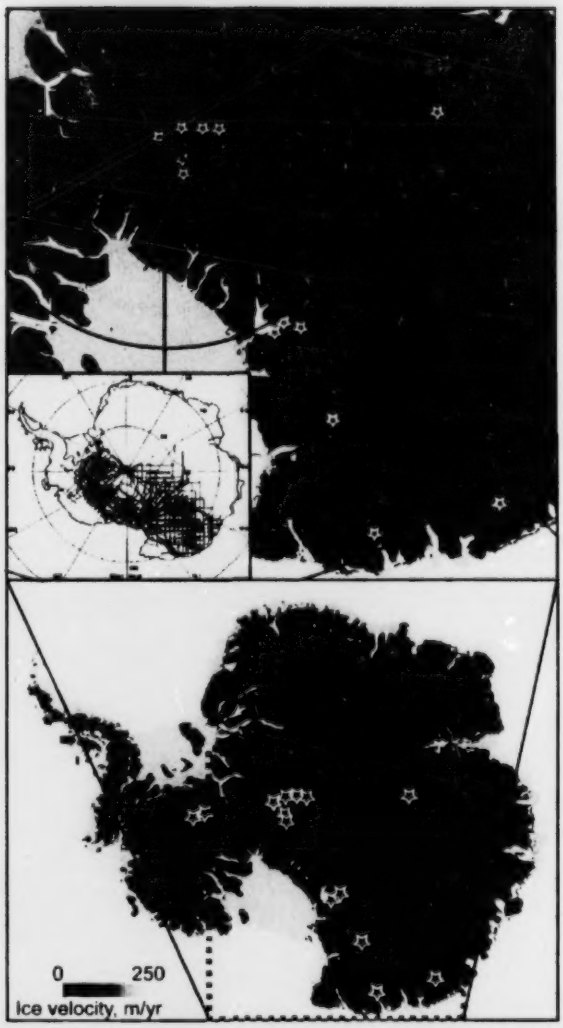

Figure 2: Ice sheet flux and the locations of known subglacial lakes (denoted as stars) around (a) half of the East Antarctic Ice Sheet where airborne radar data area available and (b) across the whole Antarctic continent

The distribution of Antarctic subglacial lakes also shows that sixteen are located close to the transition to enhanced ice-sheet flow (Siegert and Bamber, 2000; Figure 2). Several subglacial lakes thought previously to be located in the slow-moving central region of the ice sheet are, in fact, at the margins of enhanced ice flow. Subglacial lakes near to South Pole are adjacent to an outlet glacier system deep within the Antarctic continent that flows into the Filchner-Ronne Ice Shelf. This indicates that warm-based flow of ice (i.e. basal sliding and/or deformation of subglacial sediment) can be initiated near the centre of the ice sheet, and extend continuously between this region and the margin of the ice sheet where ice streams terminate. Unless the ice-sheet base becomes frozen down-stream of these lakes, which is improbable given the steady increase in ice flux calculated along these flow features, there should be a subglacial hydrological connection between the onset regions of enhanced flow, where our lakes are located, and the ice streams further downstream. Because of this, several enhanced

flow features that initiate in the inner Antarctic ice sheet can be thought of as being warm-based across their entire length. The identification of warm-based ice-sheet outlets is of value as a boundary condition to those building numerical models of the Antarctic ice sheet, since the subglacial thermal regime is critical to the flow of ice.

2.2 Canadian activities

Life in Lake Vostok

David Bird
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Looking in from the outside of the subglacial Lake Vostok system, with what little is known about conditions there, we ask whether life could exist there, and what characteristics living communities might possess if they have survived. The perennial >1,000,000-year isolation of Lake Vostok from the surface biosphere and from important energy sources is bound to make life difficult. The physical conditions of the lake include sub-zero temperature, high hydrostatic pressure, potentially rapid substrate dilution through water mixing dynamics, and low water (and nutrient) renewal rate. Furthermore, we might ask how Vostok and other subglacial lakes were colonized. How might the genetic characteristics of any potential community have been determined by the source of colonizing bacteria, and by subsequent changes since isolation from the rest of the biosphere?

The first of the physical constraints is temperature. Water temperature is suggested to be about –2.7 °C (e.g. Carmack and Wüest 2000). Sub-zero temperatures do not prohibit life as long as there is liquid water. Colder environments at the surface of the planet have been shown to contain active bacteria. In particular, bacteria are active in the antarctic Dry Valley Lakes in saline water below -8 °C (Tyler et al. 1998) and bacteria grow in brine channels in sea ice at similar temperatures (Junge et al. in press). Psychrophilic bacteria will grow in culture down to –12 °C. The record holder is a photosynthetic eukaryote specifically adapted to growth on snow, *Chlamydomonas nivalis*. Its minimum, optimum, and maximum growth temperatures are –36 °C, 0 °C, and 2 °C.

However, there is strong evidence of negative interaction between low temperature and oligotrophic conditions. Bacterial growth at very low temperature may be disproportionately inhibited at very low nutrient concentrations (Pomeroy and Wiebe 2001). Bacteria seem to need concentrated nutrients in order to grow at near-freezing temperatures, apparently due to reduced affinity (i.e. reduced ability to take up organic molecules at dilute concentrations). It is not clear, however, whether this effect will preclude growth, or merely reduce it.

The second physical constraint that deserves mention is the high hydrostatic pressure. At roughly 4 km depth under the ice and extending to 5 km maximum depth, pressure in the lake would be in the range of 350 to 450 bars. These pressures would inhibit most surface bacteria. Deep-sea bacteria include barotolerant species, which are inhibited but survive similar pressures, and barophilic species which require and thrive under these and higher pressures. To my knowledge there are no known freshwater environments with similar pressures. The deepest surface lake is Lake Baikal, at 1637 m. Thus these pressures may constitute a problem for the bacteria in Lake Vostok unless they have come in from a similarly high-pressure habitat (such as the deep rock hydrosphere).

Ecological dynamics of the microbial community in Lake Vostok will be very dependent on physical energy balances within the lake that drive the circulation. Biological communities in the lake probably depend entirely on organic carbon, nitrogen, phosphorus, oxygen and other substrate inputs from the slow movement of glacial ice across the lake. This movement is estimated at 2.2 metres per year, or roughly 6 mm per day. Rapid circulation rates (Carmack and Wüest 2000) would be detrimental to microbial communities that might develop at that ice-water interface, through dilution of incoming nutrients. It is possible that the accreted ice microbial sample is not representative of the bulk of the lake water. It may be a sample taken from the bacteria that live at the ice-water interface.

Finally, we should not overlook the lack of sunlight. It has now been shown that sunlight is not only necessary for photosynthetic production of labile organic carbon in surface waters, but it is also an important driving force in organic matter breakdown and subsequent microbial metabolism in natural systems. Refractory compounds brought to the lake in glacial ice, either from the surface or from erosion of the "drainage basin", might therefore remain refractory and inaccessible through lack of photolytic alteration.

What might the Vostok community resemble? Million-year isolation from species and gene flow with the surrounding biosphere is long from a human perspective but relatively brief in evolutionary terms. The two purely microbial domains of life (Bacteria and Archaea) have been around for more than 3 billion years, so that the million-year scale is almost incidental in that history. Tiedje (1999) points out that even very closely related bacterial species, living in the warm rich habitat of the mammalian gut, are believed to have diverged over a period of 10-100 million years. There is a good chance that the bacteria in the lake will be better adapted to cold, dark, nutrient-poor conditions, but only on the gene level and perhaps not on the species level.

A more interesting possibility is that the extreme environment of Vostok might act to select, isolate and permit the dominance of bacterial types which are normally rare, and difficult or impossible to cultivate from surface communities. We believe that our culture results from the Vostok accreted ice offer a glimpse of the nature of this community (Karl et al. 1999). The great majority of the ^{14}C-labelled acetate added to melted ice was respired; less than 0.1% was incorporated into protein as measure of growth. This suggests a community dedicated solely to survival and repair when presented with new substrates.

A Proposal for Sampling a Subglacial Lake at South Pole

Erik Blake
Icefield Instruments Inc.

I have been collaborating with David Fisher of the GSC on clean drilling technology, using a modified SIMON drill. This drill was designed for trace metal sampling, and so the objective was to reduce the surface contamination on ice cores to reduce the material that needs to be removed in order to get a good sample for analysis. It was largely an issue of changing materials and how the core is handled. The sections of the drill that contact the ice were changed from stainless steel and aluminum to virtually pure titanium and high-density polyethylene., and the cutters were changed from steel to tungsten carbon with a cobalt binder. The cutter head also has a titanium nitrite coating. It was field tested in the summer of 2000 and 60 metres of core were obtained. Some of the first analysis of the core shows 200ppt on the surface of the core. However, I suspect we were actually drilling it with steel core dogs, not the carbide ones. The real levels should be about an order of magnitude smaller. The most novel thing about this drill is that the core is actually drilled directly into a pre-cleaned polyethylene sleeve which is then capped. This becomes the transport tube for the core.

In addition to the work with David Fisher, I have submitted a proposal with Buford Price of the University of California Berkeley to do subglacial sampling in the lake near the South Pole. Our project was part of a four-pronged proposal which unfortunately did not get funded. The idea behind the proposal was to test technology in a smaller lake prior to scaling to larger lakes such as Lake Vostok. One of the advantages to South Pole Lake is that there is a lot of infrastructure already there to support the project since it is located approximately 8 km from South Pole. In the first year of the proposal we wanted to try and characterize the lake in terms of water depth and sediment thickness using seismic methods. The proposal calls for designing and testing of the drill in parallel with the lake characterization. The end result would be a "sterile drill" designed to operate beginning at 10-20 m above the ice-water interface.

There are three major components in terms of the concept of the drill: a deployment bus which never goes in the lake, a sampling sonde which of course does enter the lake, and a completion drill. The overall length is still to be determined, based on what instruments will be included.

The deployment bus is connected to the surface via a 2-conductor cable carrying 600VAC power (20kW at surface) and a communications link. It contains a control computer and data storage, power management and a backup battery, a winch for lowering the sampling sonde (120m cable), and an 18 cm diameter outer barrel.

The sampling sonde comprises an instrument and control package, water samplers, and a drop corer. The control module has a control computer and data link, a backup battery, hard disk storage for imaging, and spooled cable for the drop corer. The sensor package could include instruments for measuring CTD (conductivity, temperature and depth), pH, redox potential, dissolved carbon, and fluorescence detectors. It could also include a camera (micro/macro), a bulk sample pump with 0.2µm filter, and a depth-sounding sonar. The water samplers consist of three remotely-controlled oxygen-tight samplers (with vents). These would be modified Niskin or bag samplers. In addition, there is one pressure-sealed sampler for preserving dissolved gasses and one small cross-contamination sampler which would be triggered before the drill entered the lake. The drop corer will use spring fingers, a flap valve, and/or a piston core arrangement to hold the core. The coring device is not pressure-sealed

which may be a problem since there will be dissolved gases in the sediments that could disrupt the layering as the corer is raised to the surface.

The deployment of the completion drill is a six-fold procedure. First, using a conventional hot water drilling system, an access hole is drilled to a point near the ice-water interface. The hot water system is used to reduce the likelihood of contamination. Care must be taken to keep the hole pressure underbalanced to eliminate the possibility of hydrofracture (e.g., use deep well pumps at the 350m level).

The second stage is to freeze the drill in place. A big issue at this point is sterilization. The drill needs to be sterilized at the manufacturing facility and shipped to the site in sterile packaging. Once the sterile drill is in place, the water is pumped out to accelerate borehole closure. A final in-situ sterilization is then performed, perhaps using hydrogen peroxide (H_2O_2), although some bacteria can survive that. Alcohol is another option, but that introduces organic carbon which can interfere with subsequent sampling. It is at this stage that the cross-contamination sample is aken, to provide an indication of what was in the vicinity of the drill before the lake was entered.

The third stage of the deployment process involves the release of the completion drill. The drill is a 10kW hot-point with a penetration rate of 5.5cm/min. A question at this point is what happens to the water which results from the ice melted by the drill, and a method for venting the water to the surface needs to be developed. A sonar in the completion drill detects the ice-water interface and upon entering the lake, the drill sinks to the lake bottom or floats to the side.

The fourth step is the sampling program and retrieval of the samples. The sampling sonde is lowered via the bus winch in a controlled descent to take water samples, filter samples, and other readings. Once the controlled sampling program is complete, the sonde releases a stored cable and drops to take a core sample. The bus winch then raises the sampling sonde back into the deployment bus. A release mechanism would free the core tube if it got stuck in the sediment.

The fifth stage, sealing the hole, will be difficult technologically because ideally it would operate as an air lock. Our best idea so far is some sort of refrigeration system, perhaps using thermo-electric coolers installed on the outer barrel to create a frozen bulb at the bottom (heat pump) or a packer or other method to seal the hole.

The final step is also technologically challenging and involves the recovery of the drill and samples. The hot water drill reopens the hole to the sampler by drilling along the cable. The deployment bus barrel can be left in-situ. To prevent the hot water hose tangling with the drill cable, perhaps anti-torque skates could be placed at intervals along the hose.

The main challenges to the deployment process are the sterilization and cleaning of the drill, drilling an access hole through 3 km or more of ice, resealing the hole once the sampling program is complete, and drilling along the cable to recover the sample. There are also questions about how to handle the samples at the surface, particularly those that are environmentally sealed at 300 bars.

Lake Vostok as Tabula Rasa and Multidisciplinary Challenge

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Although physical laws apply universally, the relative importance of individual processes that operate in exotic systems and those that operate in familiar ones can differ substantially. It is therefore necessary to take a guarded approach when interpreting how exotic systems like subglacial Lake Vostok behave. What makes Lake Vostok an exotic system, apart from its inaccessibility, is the manner in which conventional geophysical elements interact to control the lake geometry and the mass and energy fluxes to and from the lake. It is doubtful that fundamental questions of lake geometry, fluid dynamics, chemical and water balance and melting and accretion processes can be understood by examining the lake, ice sheet, and lithosphere separately. I will illustrate this potential entanglement by considering a curious feature of the Vostok core from several perspectives, and exploring its possible implications.

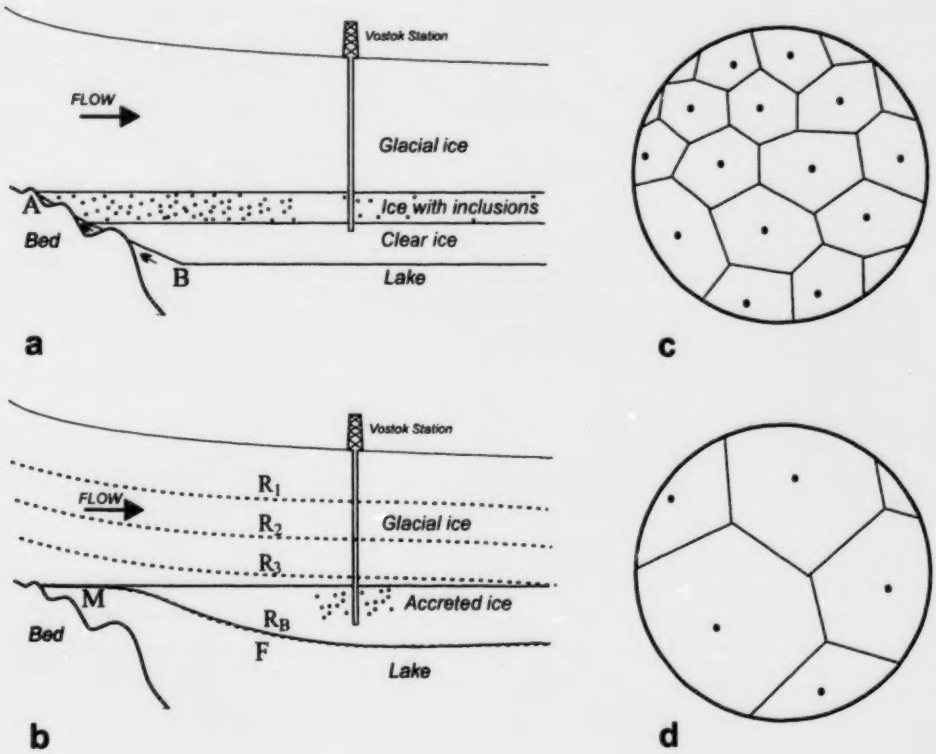

Fig.1. (a) Schematic diagram of Lake Vostok and its surroundings (after Jouzel et al., 1999). (b) Schematic diagram of radar reflecting horizons (R1, R2, R3 and RB) in the vicinity of Lake Vostok and their interpretation in terms of bottom melting (M) and freezing (F) zones (after

Siegert et al., 2000). (c) Small ice crystals with mineral inclusions that served as a nucleation centres for crystal growth. (d) Large ice crystals with mineral inclusions that served as nucleation centres for crystal growth.

Jouzel *et al.* (1999) and Souchez *et al.* (2000) note that the upper 70 metres of the lake-ice section layer in the Vostok core contains millimetre-scale mineral inclusions, "more numerous in the upper part of the lake ice" which "seem to be absent below 3609 m" (coring stopped at 3623 m). Their interpretation of the inclusion entrainment mechanism is summarized in Figure 1a. Essentially, the region near point B is assumed to be a region where ice accretion occurs and where solid inclusions from the glacier bed are frozen onto the glacier sole. Such an interpretation is supported by the Wüest and Carmack (2000) model for Lake Vostok circulation and draws substantially on the physical processes that operate beneath floating ice shelves. Convective cells rise to the highest elevation of the ice roof and rising water is subject to constitutional supercooling which leads to frazil ice formation in the rising water column. Framed in this manner, the plausible interpretation of the solid inclusions might be characterized as "oceanographically-tinted."

A glaciologically-tinted interpretation might start from the Siegert *et al.* (2000) analysis of the spacing between radar reflecting horizons (labeled R1, R2, R3 and RB in Figure 1b). Variations in the thickness of the layer between horizons R3 and RB are interpreted as evidence for melting or accretion at the ice-water contact. According to the interpretation of the radar data, the upstream (i.e. with respect to the ice flow) margin of the lake is a region of melting (M in Fig. 1b) rather than freeze-on (A in Fig. 1a) and would therefore be unconducive to entrainment of solid inclusions. From the perspective of ice flow mechanics, the upstream and downstream margins of the lake would be regions where shear stress is concentrated (Blatter *et al.*, 1998, Figs. 4 and 5) and strain heating could become appreciable. Under these circumstances, melting rather than freezing conditions would prevail. A further tantalizing observation is that for much of the lake ice section of the Vostok core there is an order-of-magnitude correspondence between the number density of inclusions n_s (number of inclusions per unit volume) and the number density of ice crystals n_x (number of ice crystals per unit volume). This could be coincidental but it might also be taken as evidence that the solid inclusions served as nucleation centres for ice crystal growth (Fig. 1c-d). Such a circumstance would be highly unusual but might signal the operation of unexpected physical processes that could best be examined through laboratory studies and computer modelling.

The fact that oceanographically and glaciologically tinted interpretations do not lead to a coherent understanding of important processes operating in the lake illustrates the necessity of an integrated approach that does not separate ice sheet mechanics, subglacial hydrology, lake dynamics and melt/freeze processes between the lake and ice sheet. Clearly, there exists a plethora of scientific challenges, many of which can be addressed without huge financial expenditures and without setting foot in Antarctica. Canada could therefore make a significant contribution to Lake Vostok science by exploiting existing strengths in computer modelling and increasing its investment in relevant field and laboratory-based studies of glaciological processes.

Ice Core Records from the Canadian Arctic and Yukon

David A. Fisher and Roy (Fritz) Koerner
National Glaciology Program, Terrain Sciences Division, GSC, NRCan

In addition to Drs. Fisher and Koerner, the glaciology group includes Mike Demuth, Jocelyne Bourgeois, Chris Zdanowicz, James Zheng, John Sekerka, and Murty Parnandi. The group's ice core program dates back to the 1970s. It provides information about the history of long term climate, atmospheric chemistry, stable isotopes, pollen, biological and other records on time resolutions of seasonal to millennial and covers the last glacial/interglacial cycle from sites all over the Arctic and the Yukon. The ice core studies add a time dimension to the regional monitoring programmes also done by the group and place the modern trends in context. The multi-proxy, multi-variable approach of ice cores allows the cause and effect relationships to be established and provides, along with the records from tree rings and other climate sensitive stratigraphies, a way of reconstructing the history of the earth's climate in great detail over the last few thousand years.

The ice core studies planned for Mt Logan and surroundings will throw light on the importance of the Pacific Northwest and the contrast between the Eastern and Western Arctic. This Logan work is lead by the GSC but is only possible because of the cooperative approach in planning, financing and execution between universities and other government institutions (University of New Hampshire, University of Maine University of Ottawa, University of Copenhagen, DFO, University of Alaska, University of Alberta, AINA, UBC, NIPR - Japan, Science Centre Kluane, Parks Canada and others).

The Arctic ice core work has recently focused on our new ultra clean drill, which provides very clean cores for the study of ultra trace metals and other "contaminants". With the rapid development of analytical methodology and drilling techniques, it is important to procure ultra clean ice cores for trace studies (metals, ions, biological parameters etc.). Up to now most laboratories working on trace metals have adopted methods for de-contaminating their ice cores. Though effective and widely accepted, these procedures use large volumes of core, and are very time consuming. Quite often a single core can only be used for trace metal analysis, leaving nothing for other types of samples. Moreover, it is difficult to control and remove penetrating contamination when handling the firn sections of an ice core. One of our goals was to significantly reduce contamination during the drilling, handling and shipping processes. The clean drill sonde is similar to an (earlier) steel version. It is modified from the SIMON drill (Terrain Sciences Division, GSC) with titanium replacing steel barrels, and providing more clearance inside to receive plastic liner inserts. Major modifications focused on the drill head, drill bits, chips guide, inner/outer barrels and core insert mechanism.

Modifications were carried out by Icefield Instruments Inc. of Whitehorse. The drill is light, sturdy and easy to operate. It will be available for cooperative projects that require ultra clean samples and where co-planning and financing is possible. We are also analyzing two recently obtained surface to bed cores from the top of the Devon Ice Cap. Possible future Arctic drill sites in the reconnaissance and planning stage are the Barnes Ice Cap (Baffin Island) and Mt Oxford (Ellesmere Island). These projects are presently in the group planning, science planning and finance building stages. Anyone interested in participating need only contact us.

The third largest water ice cap known after Antarctica and Greenland is the North Cap on Mars and the group has a small but active programme to study it. This throws light on the climate cycles of Mars, extreme ice rheology and the water (resource) cycle of Mars. The First and Second International Conferences on Mars Polar Science and Exploration were co-(convened) sponsored (along with NASA, IGS and the University of Iceland) by GSC. This work has been pursued along with Icefield Instruments Inc. and we also share in their interests in the Antarctic Lake and Europa cryobot studies.

A recent collaboration between Dave Fisher and Martin Siegert of the Bristol Glaciology Centre focuses on ancient ice exposed at the surface of Antarctica and the construction of detailed climate records on Earth and Mars. Flow of the East Antarctic Ice Sheet across the subglacial barrier of the Transantarctic Mountains' foreland, combined with sublimation of surface ice, causes ancient ice to become exposed at the ice-sheet surface. Meteorites and dust collect at the surface of the 'blue ice' zones as a consequence of long-term katabatic-wind-forced surface ablation. Here, isochronous internal layers, measured by airborne radar, are traced from two blue ice zones across >2000 km of the ice sheet to the Vostok ice core site. This allows the depth-age relationship of the blue ice zones to be established, revealing one as a prime site for a high-resolution palaeoclimate record for the last 100,000 years. The subsurface ice-sheet structure across this blue ice zone is analagous to that proposed across light and dark strips on the northern ice cap of Mars, suggesting that detailed palaeoclimate records, and ancient dust and meteorites could be collected from the Martian ice surface.

Modelled Inception and Growth of the Antarctic Ice Sheet
Nested Model Examination of Subglacial Energy Balance in the Vostok Region

Shawn J. Marshall
Department of Geography, University of Calgary

My main research area is theoretical modelling of glacier and ice sheet dynamics, and I have spent the past several years building up a three-dimensional numerical model of ice sheet thermomechanics. Studies with this tool have focused on the Laurentide and Greenland Ice Sheets to date. Together with Garry Clarke (University of British Columbia) and Kurt Cuffey (University of California-Berkeley), recent studies have examined ice sheet inception, Ice Age glacial cycles, ice stream dynamics, Eemian ice sheet/sea level reconstructions in Greenland, and deep ice deformation in Greenland ice cores. I have not yet engaged in Antarctic studies, but application of the model to East Antarctica could be relatively simple and fruitful.

A spatial-temporal hierarchy of modelling studies is needed to focus on subglacial lake evolution. Long-term studies of Antarctic Ice Sheet inception and growth can be done at relatively coarse resolution (ca. 100 km) with a 3D model. A full exploration of Eocene and Oligocene growth of the continental ice cover in Antarctica is almost within reach of high-

performance computers, and I am setting out to examine this with Andy Bush, Earth and Atmospheric Sciences, University of Alberta. Bush is a paleoclimate modeller who has adapted the GFDL-Princeton coupled ocean-atmosphere general circulation model to "deep-time" applications. This large-scale model would allow us to explore questions of the origin and age of subglacial lakes beneath the East Antarctic Ice Sheet. It is possible that some lakes were trapped and frozen beneath the advancing or nucleating ice. Such subglacial lakes would probably freeze completely over in early stages of the ice sheet evolution. As the ice sheet thickened and became a permanent fixture in East Antarctica, basal temperatures would eventually reach the melting point and basal meltwater would begin to pond in subglacial basins. Timing of subglacial lake formation in different regions would be dictated by the 3D ice sheet thermodynamics (advection, diffusion, and strain heating in the ice), air temperature and precipitation history, and the local geothermal heat flux.

Nested model studies can also be done, to zoom in on the dynamical and thermodynamic conditions in the vicinity of subglacial lakes of interest, e.g. the Vostok or South Pole regions. Such studies would employ either (a) high-resolution (ca. 2 km) 3D models that include longitudinal stress/strain mechanics, or (b) one-dimensional thermodynamic models with very high vertical resolution (ca. 1 metre at the base), set up to do point studies of the basal energy balance at select locations. Both of these approaches require large-scale 3D studies to generate boundary conditions (horizontal velocity fields, regional topographic gradients) for high-resolution modelling. The nested study can be done for a steady-state East Antarctic Ice Sheet, based on the modern geometry, or it can be done for the recent history of the ice sheet, the last 400 kyr for instance, with paleoclimatic forcing provided by the Vostok ice core. In either scenario the focus would be the energy balance at the lake-ice or bed-ice interface, to study the temporal variability and spatial patterns of warm vs. cold-based ice and melting vs. refreezing conditions. Detailed knowledge of the geothermal heat flux and convective heat fluxes in the lake would be needed for this.

A hierarchical study of this sort can be staged, with large-scale and 1D model studies used to explore the problem initially. High-resolution 3D modelling is within reach, but more sophisticated ice dynamics models must be developed and tested for this problem. This could mesh well with the general timeline of subglacial lake exploration, as more sophisticated models can be developed and brought to bear on the problem as warranted. High-resolution 3D modelling would also require detailed bedrock maps, so some field-based radar characterization might also be required for regional model development. As a final note, model-based studies could of course be conducted at Arctic test sites, given the bedrock information, to examine their utility (or lack thereof) in aiding understanding of the subglacial lake history and environment.

There are natural linkages between Antarctic modelling studies with a Lake Vostok focus and current research under the auspices of the Canadian Institute for Advanced Research (CIAR) Earth System Evolution Program. I am just beginning collaborative CIAR work on Cenozoic paleoclimate and ice sheet reconstructions in Antarctica, joint with Andy Bush, University of Alberta, and Dan Schrag, Harvard University. Other connections within the CCAR network include (a) linkages with Eddy Carmack's lake circulation model, and (b) direct linkages to the potential development of a subglacial environment laboratory (Garry Clarke, Erik Blake), which will allow controlled-experiment exploration of subglacial processes and essential data for model validation.

Subglacial – Deep Ice Research Activities

Wayne Pollard
Department of Geography, McGill University

Together with my graduate students I am involved in three activities relevant to the topic of subglacial lake and deep ice environments. My work on permafrost hydrology focuses on perennial springs on Axel Heiberg Island and their hydrologic nature, origin and geomorphology. In our search for the source of recharge for this water we consider subglacial melt water and large ice-dammed lakes as the most likely source. As we elucidate hydrologic linkages between Axel Heiberg subglacial and spring systems we will develop a better understanding of subglacial groundwater systems. (includes Dale Andersen, Chris Omelon, Lyle White, Chris McKay)

The second area involves the recent work of Derek Mueller on the microbial ecology of cryoconite structures on the Canada and White Glaciers (Mueller, D. et al. 2001). Although focusing on surface ice ecosystems this work provides insight into ice habitats. Its bipolar context will also provide information on differences in ice biodiversity between Arctic and Antarctic glacial systems.

The last area involves the evaluation of Lake Vostok as a Europa biological analog. Through the last thirty years, planetary scientists have sought terrestrial analogues for the physical, biochemical and biological processes that may be occurring on Mars and Europa. Recently, Lake Vostok has drawn the attention of researchers seeking to understand by analogy the microbial activity that could be occurring beneath the icy surface of Europa. But while "analogies" relate terrestrial fieldwork to non-terrestrial environments, there are no clear rules or criteria with which to define the appropriateness or adequacy of the ties themselves. Together with M.Sc. student Richard Soare I have been involved in a systematic assessment of criteria for planetary analogs and a review of the value of Lake Vostok as a Europa analog.

Microbial Activity Beneath Ice Sheets and its Influence on the Subglacial Environment

Martin Sharp
Department of Earth and Atmospheric Sciences, University of Alberta
Julia Foght
Department of Biological Sciences, University of Alberta

Martin Sharp has 22 years experience investigating sub-glacial processes and environments in Iceland, Alaska, Norway, the Alps, the Canadian Rockies and the Canadian high Arctic. During this time he has worked on the physical properties of sub-glacial sediments, the properties and genesis of debris-bearing basal ice sequences, and the character and behaviour of sub-glacial hydrological systems (using methods such as dye and isotopic tracer studies, meltwater hydrochemistry, sub-glacial and borehole instrumentation, and radio echo sounding). More recently, he has been interested in subglacial biogeochemistry and carbon cycling (using analyses of major ions, C, O, H, S, Sr isotopes, and dissolved organic carbon), the behaviour of Persistent Organic Pollutants and mercury in glacial systems (with David Schindler, Jules Blais, and Vincent St. Louis), and the nature and existence of microbial life in and under glaciers (with Julia Foght, Mark Skidmore and Brian Lanoil). This work has focused on the investigation of the environments in which micro-organisms occur, the types of

organisms present (using molecular and culturing techniques), their biogeochemical function and viability under in situ conditions, and evidence for in situ activity

Julia Foght is a cold regions microbiologist, with special interests in the microbial degradation of crude oil, refined petroleum products under cold conditions. She is especially interested in molecular genetic aspects of polycyclic aromatic hydrocarbon degradation by bacteria, specifically studying the factors that control degradation and methods to enhance the ability of bacteria to degrade such pollutants in the environment. This has involved isolation of bacterial strains from the environment, and mutation of their plasmid-borne and /or chromosomal genes. She has been studying crude oil degradation by mixed populations, pure cultures and genetic mutants. This work has included demonstrating the loss of parent compounds and analyzing the products of bacterial attack on crude oils, primarily using gas chromatography, mass spectrometry and radiorespirometry. She has worked in Antarctica with the New Zealanders on hydrocarbon degradation in fuel-contaminated soils. Recently she has been working with Sharp, Skidmore and Lanoil on the characterization of subglacial microbial populations from the Canadian Arctic.

In terms of future work, our basic interest is in the question "*What are microbes doing under ice sheets and how does their activity influence the chemistry of their environment ?*". Answering this question will demand work in three separate areas: molecular microbiology (where the DNA of micro-organisms is characterized without having to grow them), conventional culturing (where the activities of the organisms are directly observed or inferred by growing them), and low temperature aqueous geochemistry (to determine the energy sources and redox couples that support life and identify the impact of microbial activity on the chemistry of waters and ices within which populations of organisms are found).

While it would be possible for molecular microbiology to be conducted at the University of Alberta, it would be better for this work to be done by a specialist lab in Canada or through our collaboration with Brian Lanoil (NASA-Jet Propulsion Laboratory). Foght would aim to support this work through conventional culturing and Sharp would analyse the major ion, isotope and organic C chemistry of associated waters and ices. Our goals would be to investigate aerobic and anaerobic activities involving both heterotrophic and autotrophic processes (that respectively use organic C and fix CO_2), to assess in-situ microbial activity through culture experiments under near in-situ temperatures and pressures, and ultimately to identify the energy sources and redox couples that support life in the deep subglacial environment. This work would contribute to an ongoing effort to understand ecosystems that are supported by 'legacy' carbon, rather than primary production. Such ecosystems may have been sustained by Boreal forest carbon overridden by mid-latitude ice sheets during the Pleistocene, and may also have been critical to the maintenance of life during "snowball earth" episodes in the Proterozoic. They may also be analogues for the sorts of ecosystems that could exist beneath the Martian polar ice caps and the floating ice shelf on Europa.

Virus Indicators in Deep Ice and Sub-glacial Lakes as Indicators of Global Change

Curtis Suttle
Department of Oceanography, University of British Columbia

Few records in glacial ice can yield information on changes in biological communities and climate that have taken place over thousands to hundreds of thousands of years. One potential indicator is virus particles. Viruses are extremely small (roughly 25 to 300 nm in diameter) DNA or RNA containing particles that have no metabolism outside of their host. Without metabolism, there is no concern that their genetic composition has changed during the time they are in the ice. Extremely abundant in the biosphere, with typical concentrations of 1 to 100 million per mL in oceans and lakes, they are the most abundant biological entities on the planet. Moreover, their nucleic acids gives them distinct genetic signatures that allows examination of changes in community structure over time.

The small size and high abundance of viral particles means they form aerosols easily and can be transported in the atmosphere. Evidence that viruses have been transported and deposited in ice was demonstrated recently when genetic signatures of specific plant viruses were found as components of glacial ice from Greenland (Castello et al. 1999). Recent observations in my laboratory of 7000-year old ice from Ellesmere Island indicate that viruses are relatively abundant components (thousands per cc). This suggests that we should be able to use modern molecular approaches to follow changes in the structure of viral communities in the ice over relatively long time scales. Moreover, it should be a relatively simple matter to examine viruses in water samples that can be collected from subglacial lakes and compare their genetic signatures to extant groups of viruses.

The same approach we employed for examining genetic diversity of viral communities in seawater (Short and Suttle 2000; Short and Suttle 1999) would be used to characterize viral communities in ice cores and subglacial lakes. Techniques borrowed from molecular biology (polymerase chain reaction and denaturing gradient gel electrophoresis) are used to amplify gene fragments associated with specific groups of viruses. Analysis of these genetic fingerprints and sequences will allow the determination of how the composition of viral communities has changed over time. Changes in viral community structure are likely associated with climatic events that change the composition of the microorganisms that are the primary hosts for these viruses. As well, periods of drying or increased precipitation will likely change the types of viruses that are entrained into the atmosphere.

Ultimately it should be possible to associate specific groups of viruses with specific climatic periods on earth. In turn, this should open a window on the composition of the microbes that are the hosts for these obligate pathogens.

Polar Microbial Ecology

Warwick F. Vincent
Centre d'études nordiques, Université Laval

Our limnological research group is primarily focused on how changes in the physical environment (climate, UV, spectral irradiance, light-dark cycles, temperature, mixing) regulate lake and river ecosystems. Emphasis is on algal and microbial communities at the base of aquatic food webs, especially in the north and south polar regions where the physical environment exerts a strong influence on all ecological processes (Vincent and Hobbie 2000). We have a general interest in polar microbial ecology (e.g., Vincent 1998, Vincent and Howard-Williams 2000), including questions regarding biogeography and microbial endemism; i.e., the possibility that certain microbial species have evolved within and are largely restricted to specific geographic areas. The recent microbiological work on deep ice over Lake Vostok is especially interesting in this regard (Vincent 2000a, Vincent 2000b). My colleague Prof. Reinhard Pienitz leads a paleolimnological research team within our group, and works on the analysis of sediment cores from high latitude lakes to establish historical records of how lake and catchment properties have varied in the past (e.g., Pienitz and Vincent 2000). The ancient sediments of Lake Vostok and other subglacial lakes will ultimately provide a fascinating record of this type.

Four of our interests are potentially relevant to future work on deep ice and subglacial lakes: 1) Our observation of the physical environment involves the use and interpretation of data from a variety of instrument packages, including robotic underwater devices (autonomous underwater vehicles developed by our collaborator, Dr. Michio Kumagai at Lake Biwa, Japan) and bio-optical sensors (e.g., automated optical backscattering sensors of turbidity in instruments manufactured by RBR Ltd, Ottawa, and deployed by our group each summer in the St Lawrence River-Estuary). Aspects of this instrumentation may be relevant to the design of subglacial lake exploration systems. 2) Much of our research is focused on cyanobacteria, a group of microorganisms that are distributed throughout the world but that are especially abundant in the Arctic and Antarctica (Tang et al. 1997; Mueller et al. 2001). These organisms are phototrophic, that is their energy source is sunlight. They are therefore likely to be absent from dark, subglacial lake environments. However, our research on these communities is currently focused on the micro-environmental properties of their local habitats (Villeneuve et al. 2001), and some of these assays may be relevant to probing the microhabitats of deep ice and subglacial lakes. 3) We have an interest in how extremophiles (microbial species that live in extreme environments) survive on and within ice, and much of this work is currently taking place on the Ward Hunt Ice Shelf in the Canadian High Arctic (Vincent et al. 2000). This site contains thick ice (>10 m) floating on the sea and may be a useful location for developing technologies relevant to the exploration of deep ice and subglacial lakes (as suggested in Wuest and Carmack 2000). Such work would also help us better understand the Ward Hunt cryo-ecosystem which appears to be the remnant of a much larger ice shelf system that occurred along the northern Ellesmere Island coastline at the beginning of the 20th century (Vincent et al 2001). 4) We have a general interest in the environmental protection of high latitude lakes and their catchments and have contributed to the development of environmental codes of conduct for research in such areas (e.g., Vincent 1996).

3.0 Advancing Canadian Interests in Subglacial Lake and Deep Ice Research in Antarctica

Nicole Couture, Rapporteur

During the presentations and the associated discussions, a number of themes arose. These became the focus of the latter half of the workshop.

Canadian expertise and opportunities for future research

A number of scientific and technological challenges must be overcome before sampling of subglacial lakes becomes a reality. Many scientists anticipate that at least a decade will pass before many of these issues are resolved. In the meantime, there are many opportunities for research. Workshop discussions identified a number of specific fields where Canadians might focus their efforts. Not all of the workshop participants are currently involved specifically in exploration of subglacial lakes or deep ice, but much of their research is directly applicable.

Technology

A number of technologies need to be developed for sampling subglacial lakes. For instance, a Canadian company has developed "clean" hot water access drills; however, as yet they can only penetrate through approximately 2.5 km of ice, and further work is required to drill through 3 or 4 km to reach the lakes beneath the East Antarctic Ice Sheet. Methods of sealing the access hole following sampling still need to be developed. Standard oceanographic instrumentation could be used for much of the in situ measurements in the lakes, although there is concern that they may not be sensitive enough for such an environment. Refinement of such instruments therefore presents opportunities for technological development. More sophisticated instrumentation for in situ sampling of ice, water and sediments, possibly using nano-technology, offers additional challenges. Return sample technology is also an issue and research could be focussed on resolving problems resulting from the great pressure differences, for example. Research into ROVs and sensors for underwater work is also needed. RADARSAT data is available and being used by several researchers both at home and abroad. Canadians could play a larger role in this area.

Microbiology

Canadian scientists are well versed in the analysis of microbial communities in a frozen environment and their research has included metabolic assays, live/dead assays, biomass estimators, genetic characterization, and analysis of biogeochemical function. This expertise can be applied to gaining a better understanding of the microbial diversity and the structural function of the microbial communities in subglacial lakes and sediments, in the overlying ice, and at the surface. Culturing microorganisms from the lakes presents a challenge and experimental techniques for analysis need to be developed.

Modelling

Canadian scientists seek to improve understanding of the dynamics of the ice sheet itself through the use of high definition altimetry and the development of improved 3D thermo-mechanical models. Opportunities also exist for coupling ice dynamic models with 3D time-dependent circulation models of the lakes and subglacial hydrological models. Modelling studies of subglacial environments can be advanced by using existing physical, chemical, and

biological data sets from field studies as inputs or by establishing controlled laboratory experiments. For instance, the melting/freezing processes at the roof of subglacial lakes warrant further research. Possible laboratory studies could include the effect of ice properties on microbial habitat and the role of water impurities in ice nucleation and growth processes in subglacial lakes.

Modelling can be a powerful tool in gaining better understanding of complex processes and in planning relevant field and laboratory experiments. This is especially true when dealing with exotic environments such as subglacial lakes where we have a paucity of field data, and where it is difficult and expensive to obtain additional field information.

Environmental concerns

Some environmental groups have expressed opposition to subglacial lake exploration due to the risk of contaminating the pristine environment of the lakes. Scientists planning subglacial lake exploration must address and alleviate these concerns. Environmental considerations need to be addressed not only in terms of drilling technologies, but also in terms of environmental impacts, modelling and remediation, and protocols. Canadians have helped to establish environmental codes of conduct for high latitude lakes and catchment basins, and there is interest in continuing this work. Bio-remediation studies also offer opportunities, as do those focusing on the distribution and spread of contaminants within the lakes and through their catchment basins. Decontamination of material both entering and exiting the lakes is of particular concern and procedures for doing so need to be elaborated. Environmental concerns must also be kept in mind when developing new exploration and sampling technologies.

Arctic research as a prelude to Antarctic subglacial and deep ice research

Easy access to a variety of glacial environments in the Canadian Arctic was identified as a major advantage for Canada's contribution to the exploration of subglacial lakes and deep ice. In an international context, our current and future studies in the Arctic and in the Saint Elias Mountains, Yukon can prove the credibility and applicability of our research to the field. The easy accessibility and lower cost of working in Northern Canada make it easier for Canadians to conduct their research and testing programs. It will also open new opportunities to develop international cooperation and partnerships, as scientists from other countries may want to benefit from the same advantages. The report from the 1999 SCAR workshop in Cambridge specifically recommended that more accessible analogous settings such as those available in northern regions be used as test sites for new technologies. A number of sites in the Canadian Arctic were proposed as being good analogue settings, including the Ward Hunt ice shelf, Phantom Lake, the Cadogan Glacier, and John Evans Glacier.

Communication at both the national and the international levels

The CCAR newsletter, with a circulation of more than 400, was recognized as a vehicle for disseminating information about developments and opportunities for subglacial and deep ice research. However, this was seen as being not proactive enough. It was suggested that a web-based network of interested scientists be established, to include workshop participants and those unable to attend, and others whom we did not know. The network would initially serve to facilitate exchange of information and ideas and provide the primary point of contact for international organizations involved in subglacial lake and deep ice research. It would operate under the auspices of the CPC. A steering committee comprised of Warwick Vincent and

Wayne Pollard (the outgoing and incoming chairs, respectively, of CCAR) was set up to explore this option.

Funding opportunities

There are several potential funding sources to support research of this kind. The National Science and Engineering Research Council of Canada (NSERC) would be the primary source of funding for university-based research. It has several relevant programs, including the Networks program, the Canadian Fund for Innovation, the Collaborative Research Opportunities, and the Northern Initiatives program. Some of these fund workshops to plan and develop research programs. Government scientists may obtain funding from science-based departments: Natural Resources Canada (NRCan -- through Polar Continental Shelf's Canadian Arctic-Antarctic Exchange Program), Environment Canada, and the Department of Fisheries and Oceans (DFO). Funds may also be obtained from the Canadian Space Agency's Space Life Sciences concept and Ground Studies program. The Department of Foreign Affairs and International Trade (DFAIT) has programs to support strengthening of science and technology links with the broader international community, and these may be applicable to the initiation and planning phases of the research program.

The above funding agencies are important for the academic community and for government scientists, but the private sector also has opportunities for funding through the National Research Council and the Department of Industry. NSERC's Industrial Awards could be used for technology development

Finally, territorial governments may be willing to fund some activities in the North, however it would be important to emphasize the Arctic research as a starting point for global science and to underline educational or public extension components of the research.

In the initial phases of the program, it is anticipated that funding will come mainly from Canadian sources, but some contributions may come from international partners participating in joint programs. The later phases with large and expensive field operations in Antarctica would likely require a major international consortium.

4.0 Closing remarks

Warwick Vincent, Chair, CCAR

This meeting has drawn attention to the diversity of expertise in 'deep-ice' related research and technology development across Canada, and the talent available for a Canadian contribution to international work in this area. It seems that a new drilling program to sample subglacial lakes in Antarctica is likely to be some years off, as considerable research and development activities must first be accomplished. Much of this developmental work could be done at analogous and more accessible field locations, and in this context it makes sense to build up Canadian research capacity (with international collaboration) in the Canadian North with a view towards later extreme-ice initiatives in the south polar region. In addition to fieldwork, there are also important modelling and laboratory studies to complete.

A common theme for all participants in this workshop is a research interest in thick (deep) ice systems: glaciers, ice sheets, ice shelves, ground ice, etc. For some participants, the focus of interest is more the upper ice surface than processes at the bottom, liquid water micro- and macro-environments rather than the surrounding ice, coastal thick-ice systems rather than the polar plateau, sampling technology rather than sample analysis, or modelling rather than field measurements. Any network of the type discussed here should try to embrace this diversity of interests, with a clear link to life in, on, or under extreme ice environments. Such a network would logically focus on building up science and technology capacity in the North, with Antarctic activities a longer-term goal.

Overall, Canada is in a strong position to become more involved in research into subglacial lakes and deep ice. With the existing Canadian expertise we are well poised to take advantage of the numerous challenging opportunities, and there are several niches that can be developed. The logistical and financial impediments to becoming involved in Antarctic research are mitigated by relatively easy access to sites in the Arctic for field research and testing programs. The establishment of a working group on subglacial lake and deep ice exploration will assist in consolidating and expanding Canadian research interests, both nationally and internationally.

In closing, I would like to thank all the people who made this workshop possible: Olav Loken, secretary to CCAR, for ensuring the smooth organization and running of this productive meeting, Nicole Couture for her excellent work as rapporteur, and all the participants at the meeting for their stimulating presentations and input. I thank the Canadian Polar Commission for the use of their facilities and their ongoing support of CCAR activities, and the Department of Foreign Affairs and International Trade who in combination with CPC funded this meeting. If you have additional comments on issues raised in this report, we would be very pleased to hear from you.

References Cited

(Names of Canadian scientists are underlined)

Abyzov, S.S., Mitskevich, I.N. and Poglazova, M.N. 1998. Microflora of the deep glacier horizons of central Antarctica. *Microbiology* 67, 66-73.

Blatter, H., G. K. C. Clarke and J. Colinge. 1998. Stress and velocity fields in glaciers: Part II. sliding and basal stress distribution. *Journal of Glaciology*, 44, 457-466.

Carmack, E. and J. Wüest. 2000. Reckoning Lake Vostok. *Newsletter for the Canadian Antarctic Research Network* 10: 1-2.

Castello, J.D., S.O. Rogers, W.T. Starmer, C.M. Catranis, L. Ma, G.D. Bachand, Y. Zhao, J.E.Smith 1999: Detection of tomato mosaic tobamovirus RNA in ancient glacial ice. *Polar Biol.* 22: 207-212

Cuffey, K. M. and S. J. Marshall, 2000. Substantial contribution to sea-level rise during the last interglacial from the Greenland Ice Sheet. *Nature*, 404, 591-593.

Dowdeswell, J.A. and Siegert, M.J., 1999, The Dimensions and topographic setting of Antarctic subglacial lakes and implications for large-scale water storage beneath continental ice sheets: *Geological Society of America Bulletin*, 111, 254-263.

Gorman, M.R. and Siegert, M.J., 1999, Penetration of Antarctic subglacial lakes by VHF electromagnetic pulses: information on the depth and electrical conductivity of basal water bodies: *Journal of Geophysical Research*, 104, 29311-29320.

Jean Baptiste, P., Petit, J.R., Lipenkov, V.Ya., Raynaud, D. and Barkov, N.I. 2001. Helium isotope in deep Vostok ice core (Antarctica): constraints on hydrothermal processes and water exchange in the subglacial lake, *Nature*, in press.

Jouzel, J., and 9 authors. 1999. More than 200 meters of lake ice above subglacial LakeVostok, Antarctica. *Science*, 286, 2138-2141.

Junge, K., Krembs, C., Deming, J., Stierle, A., Eicken, H. A microscopic approach to investigate bacteria under in-situ conditions in sea-ice samples. *Ann. Glaciol.*, 33, in press.

Kapitsa, A., Ridley, J.K., Robin, G. de Q., Siegert, M.J., and Zotikov, I., 1996, Large deep freshwater lake beneath the ice of central East Antarctica: *Nature*, 381, 684-686.

Karl, D.M., D.F. Bird, K. Björkman, T. Houlihan, R. Shackelford, and L. Tupas. 1999. Microorganisms in the accreted ice of Lac Vostok, Antarctica. *Science* 286: 2144-2147.

Lanoil, B.D., M. Sharp, S.P. Anderson, M.T. La Duc, J. Foght, and K.H. Nealson. 2001. A comparative study of microbial communities under two glaciers. 101st Annual Meeting American Society for Microbiology, Orlando FL (abstract accepted)

Lipenkov, V.Ya and Barkov N.I. 1998. Internal structure of the Antarctic ice sheet as revealed by deep core drilling at Vostok station, in Lake Vostok Study: Scientific Objectives and technological requirements, Proceeding of St Petersburg meeting , Arctic and Antarctic Research Institute, March 1998, p 31-33.

Marshall, S.J., and Clarke, G.K.C. 1997. A continuum mixture model of ice stream thermomechanics in the Laurentide Ice Sheet 1. Theory. *Journal of Geophysical Research*, 102(B9), 20,599-20,614.

Marshall, S. J. and Cuffey, K. M. 2000. Peregrinations of the Greenland Ice Sheet divide in the last glacial cycle: Implications for central Greenland ice cores. *Earth and Planetary Sciences Letters*, 179, 73-90.

Mueller, D., Vincent, W.F., Pollard, W.H. & Fritsen, C.H. 2001. Glacial cryoconite ecosystems: A bipolar comparison of algal communities and habitats. In: Lhotsky, O., Elster, J., Seckbach, J., & Vincent, W.F. (eds) Algae in Extreme Environments. Nova Hedwigia (in press).

Oswald, G. and Robin, G. 1973, Lakes beneath the Antarctic Ice Sheet: *Nature*, 245, 251-254.

Petit, J.R., I. Basile, J. Jouzel, N.I. Barkow, V. Ya. Lipenkov, R.N. Vostretsov, N.I. Vasiliev, C. Rado, 1998. Preliminary investigations and implications from the 3623 metres Vostok deep ice core studies. *Lake Vostok Study: Scientific Objectives and Technological Requirements, International Workshop*, Arctic and Antarctic Research Institute, St. Petersburg, Russia, 43.

Petit, J.R., J. Jouzel, R. D. Raynaud, N.I. Barkow, J.M. Barnole, I. Basile, M. Benders, J. Chappellaz, M. David, G. Delaygue, M. Delmotte, V.M. Kotlyakov, M. Legrand, V. Ya. Lipenkov, C. Lorius, L. Pepin, C. Ritz, E. Saltzmann, and M. Stievenard, 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, 399, 429-436.

Pienitz, R. & Vincent, W.F. 2000. Effect of climate change relative to ozone depletion on UV exposure in subarctic lakes. *Nature* 404: 484-487.

Pomeroy, L.R. and W.J. Wiebe. 2001. Temperature and substrates as interactive limiting factors for marine heterotrophic bacteria. *Aquat. Microb. Ecol.* 23: 187-204.

Priscu, J. C., and 12 authors. 1999. Geomicrobiology of subglacial ice above Lake Vostok, Antarctica. *Science*, 286, 2141-2144.

Short, S.M. and C.A. Suttle. 1999. Use of the polymerase chain reaction and denaturing gradient gel electrophoresis to study diversity in natural virus communities. *Hydrobiologia* 401:19-33

Short, S.M. and Suttle, C.A. 2000. Denaturing gradient gel electrophoresis resolves virus sequences amplified with degenerate primers. *BioTechniques* 28:20-26

Siegert, M.J. Antarctic subglacial lakes, 2000, *Earth Science Reviews*, 50, 29-50.

Siegert, M.J. and Bamber, J.L., 2000, Subglacial lakes at the heads of Antarctic ice stream tributaries. *Journal of Glaciology*, 46, 702-703.

Siegert, M.J. and Dowdeswell, J.A., 1996, Spatial variations in heat at the base of the Antarctic Ice Sheet from analysis of the thermal regime above sub-glacial lakes: *Journal of Glaciology*, 42, 501-509.

Siegert, M.J. and Ridley, J.K., 1998a, An analysis of the ice-sheet surface and subsurface topography above the Vostok Station subglacial lake, central East Antarctica: *Journal of Geophysical Research*, 103, 10195-10207.

Siegert, M.J., and Ridley, J.K., 1998b, Determining basal ice sheet conditions at Dome C, central East Antarctica, using satellite radar altimetry and airborne radio-echo sounding information: *Journal of Glaciology*, 44, 1-8.

Siegert, M.J., Dowdeswell, J.A., Gorman, M.R., and McIntyre, N.F., 1996, An inventory of Antarctic sub-glacial lakes: *Antarctic Science*, 8, 281-286.

Siegert, M.J., Kwok, R., Mayer, C. and Hubbard, B., 2000. Water exchange between subglacial Lake Vostok and the overlying ice sheet: N*ature*, 403, 643-646

Sharp, M., Parkes, J., Cragg, B., Fairchild, I.J., Lamb, H. and Tranter, M. 1999. Widespread bacterial populations at glacier beds and their relationship to rock weathering and carbon cycling. *Geology* 27, 107-110.

Short and Suttle 1999, *Hydrobiologia* 401, 19-32

Short and Suttle 2000, *Biotechniques* 28, 20-26

Skidmore, M.L., Foght, J.M., and Sharp, M.J. 2000. Microbial life beneath a High Arctic glacier. *Applied and Environmental Microbiology* 66, 3214-3220.

Souchez, R., J. R. Petit, J.-L. Tison, J. Jouzel and V. Verbeke. 2000. Ice formation in subglacial Lake Vostok, Central Antarctica. *Earth and Planetary Science Letters*, 181, 529-538.

Tang, E.P.Y., Tremblay, R. & Vincent, W.F. 1997. Cyanobacterial dominance of polar freshwater ecosystems: are high latitude mat-formers adapted to the low temperature environment? *Journal of Phycology* 33: 171-181.

Tiedje, J.M. 1999. Exploring microbial life in Lake Vostok. Pp. 19-21, in Lake Vostok Workshop: Final Report. Lake Vostok : A curiosity or a focus for interdisciplinary research. (NSF sponsored workshop, Washington, DC, Nov. 7 & 8, 1998).

Tyler, S.W., P.G. Cook, A.Z. Butt, J.M. Thomas, P.T. Doran, and W.B.Lyons. 1998. Evidence of deep circulation in two perennially ice-covered Antarctic lakes. *Limnol. Oceanogr.* 43: 625-635.

Villeneuve, V., Vincent, W.F. & Komarek, J. 2001.Community structure and microhabitat characteristics of cyanobacterial mats in an extreme high Arctic environment: Ward Hunt Lake (lat. 82.8 °N). In: Lhotsky, O., Elster, J., Seckbach, J., & Vincent, W.F. (eds) Algae in Extreme Environments. (in press).

Vincent, W.F. 1988. Microbial Ecosystems of Antarctica. Cambridge University Press, United Kingdom. 304 pp.

Vincent, W.F. (ed.) 1996. Environmental Management of a Cold Desert Ecosystem: the McMurdo Dry Valleys, Antarctica. Desert Research Institute, University of Nevada Special Publication 55 pp.

Vincent, W.F. 1999: Antarctic Biogeochemistry: Icy life on a hidden lake. *Science* 286: 2094-95.

Vincent, W.F. 2000a. De la vie dans le lac Vostok? *La Recherche*, Mar.14-16.

Vincent, W.F. 2000b. Evolutionary origins of Antarctic microbiota: invasion, selection and endemism. *Antarctic Science* 12: 374-85

Vincent, W.F. & Hobbie, J.A. 2000. Ecology of Arctic lakes and rivers. In: M. Nuttall and T. V Callaghan (eds) The Arctic: Environment, People, Policies, Harwood Academic Publishers, U.K. p. 197-231.

Vincent, W.F. & Howard-Williams, C. 2000. Life on Snowball Earth. *Science* 287: 2421.

Vincent, W.F., Gibson, J.A.E. & Jeffries, M. 2001. Ice shelf collapse, climate change and habitat loss in the Canadian High Arctic. *Polar Record* 37: 133-142.

Vincent, W.F., J.A.E. Gibson, Pienitz, R., Villeneuve, V., Broady, P.A., Hamilton, P.B. & Howard-Williams, C. 2000 Ice shelf microbial ecosystems in the high Arctic and implications for life on snowball earth. *Naturwissenschaften* 87: 137-141.

Wüest, A., and E. Carmack. 2000. A priori estimates of mixing and circulation in the hard-to-reach water body of Lake Vostok. *Ocean Modelling*, 2, 29-43.

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APPENDIX B - List of Acronyms

CCAR - Canadian Committee for Antarctic Research
CFI - Canadian Fund for Innovation
CGU - Canadian Geophysical Union
CMOS - Canadian Meteorological and Oceanographic Society
COMNAP - Council of Managers National Antarctic Programmes
CPC - Canadian Polar Commission

DFAIT - Department of Foreign Affairs and International Trade (Canada)
DFO – Department of Fisheries and Oceans (Canada)
DOE – Department of the Environment (Canada)

GSC - Geological Survey of Canada

IASC - International Arctic Science Committee
IGS - International Glaciological Society

NASA - National Aeronautics and Space Administration
NIPR – National Institute of Polar Research (Japan)
NRCan - Natural Resources Canada
NSERC - National Sciences and Engineering Research Council of Canada
NSF - National Science Foundation

PCSP - Polar Continental Shelf Project

ROV - remotely operated vehicle

SCAR - Scientific Committee on Antarctic Research
SSHRC - Social Science and Humanities Research Council